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Suitable Method (Empirical Analytical and Numerical Method) to Evaluate the Requirements for the Elephant Feet, Temporary Invert and permanent Invert

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I. INTRODUCTION

A. *Objective of Thesis*

As per NATM philosophy, the controlling the deformation is important part of the NATM philosophy and the same should be done in construction stage.

In soft ground conditions during heading excavation, techniques like **Elephant's foot, micro-piles, and temporary invert** are recommended. These methods help to control the deformation through ring closure and provide significant support for the top heading shell. Additionally, Elephant's foot and micro-piles ensure stability throughout the benching phase, making the excavation process more secure and effective.

The use of elephant's feet and micro piles is a specialized technique in tunnelling. The elephant's feet refers to the widened base of top heading support system distributes loads more effectively, preventing excessive settlement. Micro piles are small-diameter, high-strength steel pipes or bars drilled and grouted into the ground to provide additional support to the structure.

while constructing tunnels, maintaining stability during excavation is important. The top heading method involves excavating the upper portion of the tunnel first, followed by the lower sections. During this process, it's essential to support the newly exposed surfaces to prevent collapses or excessive deformation. The application of temporary and permanent invert closures helps manage these challenges.

An invert is the lowest point inside the tunnel cross-section, and closing it off temporarily or permanently provides a solid base and resists the inward pressures from the surrounding ground, which can lead to "squeezing" conditions. Squeezing occurs when the tunnel walls deform inward due to high pressure from the surrounding rock or soil. Implementing these measures helps maintain tunnel stability and ensures safe and efficient construction progress.

Despite their benefits, the implementation of techniques such as the Elephant's Foot, micro-piles, temporary invert and permanent invert in real projects often leads to debates due to the associated costs and time requirements.

- Cost Implications: The use of these advanced support techniques can significantly increase the overall cost of the project. This includes the cost of materials, specialized equipment, and additional labour required for their installation.
- Time Requirements: Installing these support systems can also extend the project timeline. The additional steps involved in setting up micro-piles or constructing a temporary invert require careful planning and execution, which can delay the overall project completion.
- Technical Complexity: Implementing these techniques requires specialized knowledge and expertise. Ensuring that they are installed correctly and function as intended adds another layer of complexity to the project.

Considering the significance and challenges associated with the implementation of the Elephant's Foot, micro-piles, temporary invert and permanent invert in soft ground tunnelling conditions, the primary objective of this thesis is to determine the actual requirement based on empirical, analytical and numerical method.

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II. OVERVIEW (PROJECT DETAIL)

The above thesis has been done based on the actual project as mentioned below;

A. *Typical Cross-Section*

The proposed typical cross section of the carriage way consists of the following main elements:
Clearance profile as defined in below figure.

- Walkway width = 1200mm/750mm)
- Walkway height =2.5m
- Paved shoulder = 1500.0m as per tender document.
- Shyness= 500m
- Driving lane: width = 3500mm +3500mm
- Height in driving lane 5500 mm

The cross-section contour of the tunnel is formed by a guideline in a three centres arch, allowing the clearance profile to the vertical axis of the tunnel to have greater height, satisfying the needs of ventilation with the ventilation ducts installation. The typical cross section for the tunnel is given below.

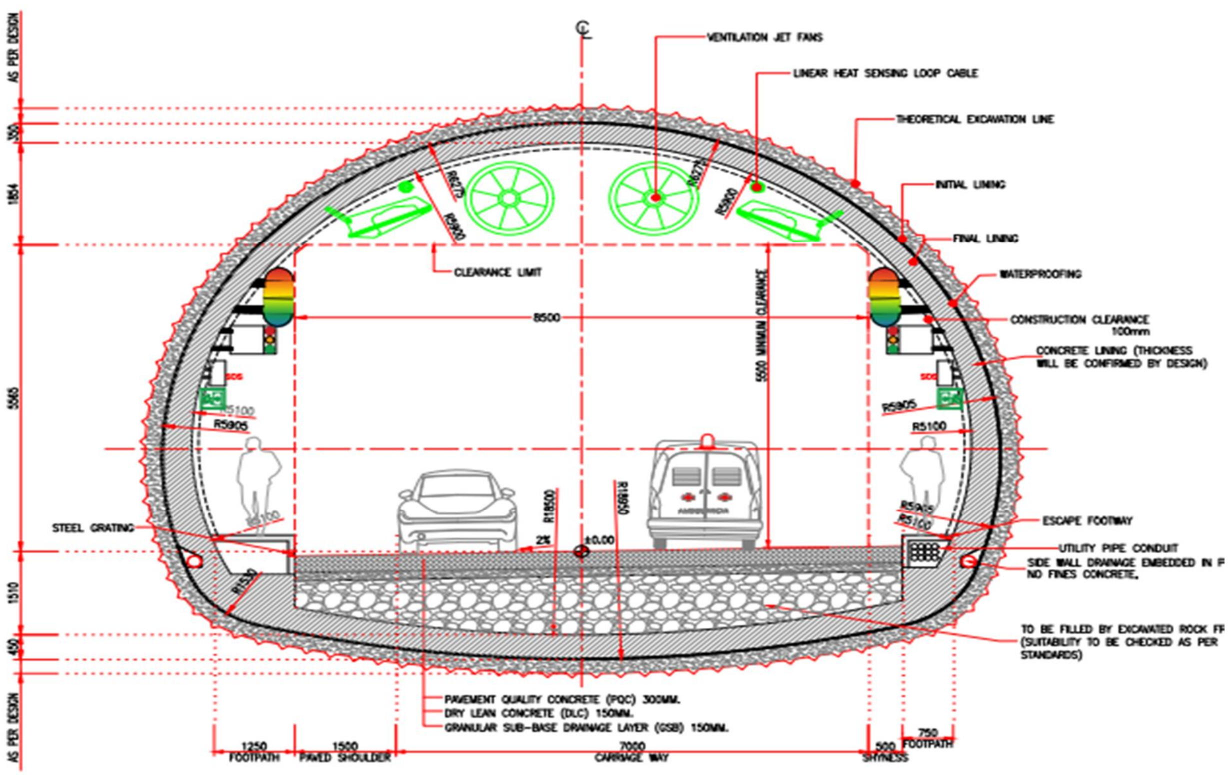

Figure-1 (Typical Cross Section)

III. GEOLOGICAL/GEOTECHNICAL EVALUATION

Engineering Geology & Geotechnical study plays substantial role during design and construction stage of any tunnel project. This is because of the uncertainty and risk involved in the tunnel /underground project. Engineering geological & geo-technical investigations of tunnel projects are of paramount importance in understanding the geological set up of varied terrains and their geo-dynamic development.

During site reconnaissance following ground types were identified around the tunnel alignment:

- Unconsolidated to poorly consolidated pebbly-boulder conglomerate bed;
- Thickly bedded semi-consolidated to well consolidated pebbly-boulder conglomerate bed;
- Friable and unconsolidated Mudstone/Claystone/Siltstone with sand layers interbedded with conglomerate bed.

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A. Field Inspection

Geological field survey was carried out on the entire project area to understand the Geology and Geo-mechanics which will be encountered at site area.

Boulder beds in contact with a layer of loosely consolidated sand type of material near the tunnel loction are shown in below figure.

Figure-2 (Ground Condition)

B. Geotechnical Classification and Design Parameters

Classification of rock mass in such type of ground types becomes a challenging job, the rock mass rating criteria like RMR, Q-system do not work in boulder beds and River borne material.

Hence the ground mass in the area has been classified on the basis of bimsoil and bimrock. The term bimrocks (block-in-matrix rocks) was coined by Medley in 1994 to generically indicate mixtures of rocks, composed of geotechnically significant blocks within a bonded matrix of finer texture (Medley 1994).

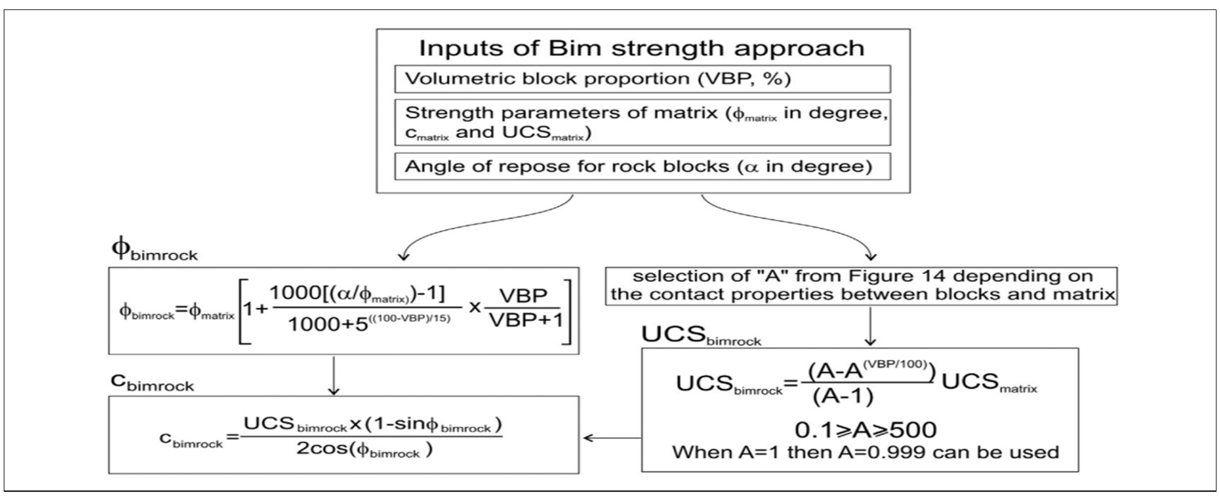
In this definition, the words "geotechnically significant" indicate that a sufficient mechanical contrast between the blocks and matrix must exist and that block sizes and content must contribute to the overall strength of the geomaterial at the scale of engineering interest, Lc (Medley 2001, 2007a).

Classification on the basis of Matrix (In reference of paper of bimrock and bimsoil)

Factor	P-1	P-2	P-3
	Cementation-Good	**Cementation-Fair**	**Cementation-Poor**
UCS (in matrix, MPa)	>5	1~5	0~1
Cementation	Combination between breccia and matix	Combination between breccia and matrix	Separation between breccia and matrix
Condition of tunnel surface	Scratched due to a hit of rock hammer, and no peeling off with a knife	Crushed by a hit of rock hammer, and peeling off with a knife	Pressed with a nail
Wet condition	Complete drying or with moisture	Wetting	Water drops fall
Slake durability index (I_{d3})	>60	<60	<60

The strength of geological materials is a fundamental property used in the design of civil engineering works; including projects constructed in complex geological mixtures or fragmented rocks such as mélanges, fault rocks, coarse pyroclastic rocks, breccias and sheared serpentines. These and other, often chaotic, mechanically and/or spatially heterogeneous rock masses are composed of relatively strong rock blocks surrounded by weaker matrix rocks. These common rock mixtures, known as bimrocks (block-in-matrix-rocks) or bimsoils (when the matrix material is soil-like) are very difficult to evaluate. It is almost impossible to recover high quality, undisturbed drill core samples or to prepare laboratory specimens perform laboratory studies and evaluate geo-mechanical parameters such as cohesion, internal friction angle and uniaxial compressive strength from these complex mixtures. The strength and deformation properties of geological masses are used as crucial input parameters during design stage of engineering works such as tunnels.

Empirical equations useful for predicting the strength of bimrocks were devised, which depend on practical charts and input parameters, such as parameter "A", defined to relate the contact strength between matrix and blocks. All the empirical equations and parameters are taken from the paper, "An approach to predicting the overall strengths of unwelded bimrocks and bimsoils Kalender et al, Engineering Geology 183 (2014) 65–79."



The above mentioned flow diagram for use of Bim Strength (In reference of paper of bimrock and bimsoil)

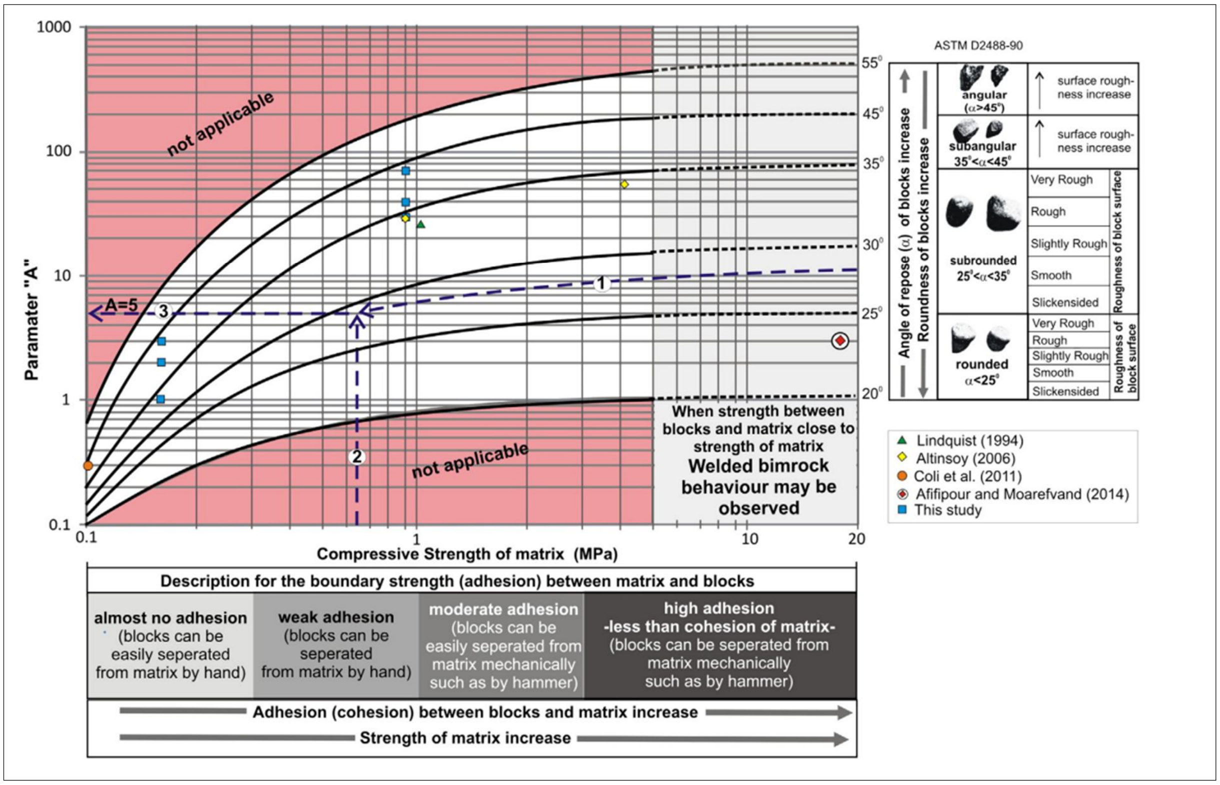


Figure 03: Graph showing relationship between Compressive Strength of matrix and Adhesiveness of matrix.

The table shows the output parameters obtained from the empirical relations used above to get the desired geotechnical parameters.

Sr no	Parametrs	Value	Unit	Remraks
1	Volumetric Block Proportion	30	%	
2	Cohesion of Matrix	0.045	Mpa	
3	Friction angle of Matrix	32	deg.	
4	UCS of matrix	0.162	Mpa	
5	A value	4		
6	Angle of repose of rock blocks	30	deg.	
7	**UCS of BIM rock**	**0.13**	**Mpa**	$UCS_{bimrock}=\frac{(A-A^{(VBP/100)})}{(A-1)}UCS_{matrix}$
8	**Friction angle of BIM rock**	**31.32**	**deg.**	$\phi_{bimrock}=\phi_{matrix}\left[1+\frac{1000[(\alpha/\phi_{matrix})-1]}{1000+5^{((100-VBP)/15)}}\times\frac{VBP}{VBP+1}\right]$
9	**Cohesion of BIM rock**	**0.038**	**Mpa**	$c_{bimrock}=\frac{UCS_{bimrock}\times(1-\sin(\varnothing_{bimrock}))}{2\cos(\varnothing_{bimrock})}$.

The parameters used in analysis are followings

- Friction angle:-30^0
- Cohesion=40 kpa
- Deformed modulus (E)) -200mpa

IV. METHOD TO DETERMINE

In soft ground tunnelling, determining the requirements for support systems such as the elephant foot, temporary invert, and permanent invert is crucial for maintaining tunnel stability and ensuring safety. These requirements can be determined using several methods, each with its own approach and applications.

A. Empirical Method

The empirical method relies on experience and observational data from past tunnelling projects. It uses established guidelines and rules of thumb that have been developed based on the performance of previous tunnels in similar ground conditions. Key aspects include:

Case Histories: Reviewing past projects with similar geological conditions to understand the effectiveness of various support measures.

Ground Classification Systems: Systems like the RMR (Rock Mass Rating) or Q-system can provide guidance on the type and amount of support required based on ground conditions.

B. Analytical Method

The analytical method involves theoretical calculations and principles of soil and rock mechanics to determine the support requirements. It includes:

Stress Analysis: Calculating the stresses and deformations in the ground surrounding the tunnel using classical soil and rock mechanics theories.

Load Calculations: Determining the loads acting on the support structures and assessing their stability.

Simplified Models: Using simplified mathematical models to predict ground behaviour and support needs.

C. Numerical Method

The numerical method involves the use of computer-based simulations to model the behaviour of the ground and the tunnel. This method is more sophisticated and can provide detailed insights.

D. Choice of Method

The choice of method depends on several factors such as the complexity of the ground conditions, the availability of data, and the resources available for the project. Often, a combination of these methods is used to achieve a reliable and robust design.

Empirical Method Suitable for preliminary design and in cases where quick decisions are needed.

Analytical Method Useful for straightforward conditions and where detailed theoretical understanding is beneficial.

Numerical Method Ideal for complex ground conditions and when detailed, accurate predictions are necessary.

By combining these methods, engineers can develop a comprehensive understanding of the support requirements for a tunnel, ensuring safety and stability throughout the construction and operational phases.

V. EMPIRICAL METHOD OF CALCULATION

The empirical method relies on experience and observational data from past tunnelling projects. It uses established guidelines and rules of thumb that have been developed based on the performance of previous tunnels in similar ground conditions.

A. Empirical Method as per Hoek (200)

As per literature (BIG TUNNELS IN BAD ROCK, By Evert Hoek,The Thirty-Sixth Karl Terzaghi Lecture) the following support system tabulated considering the weak squzzing problem.

As shown in below Figure, Hoek (2000) suggests the following measures with respect to quizzing condition.

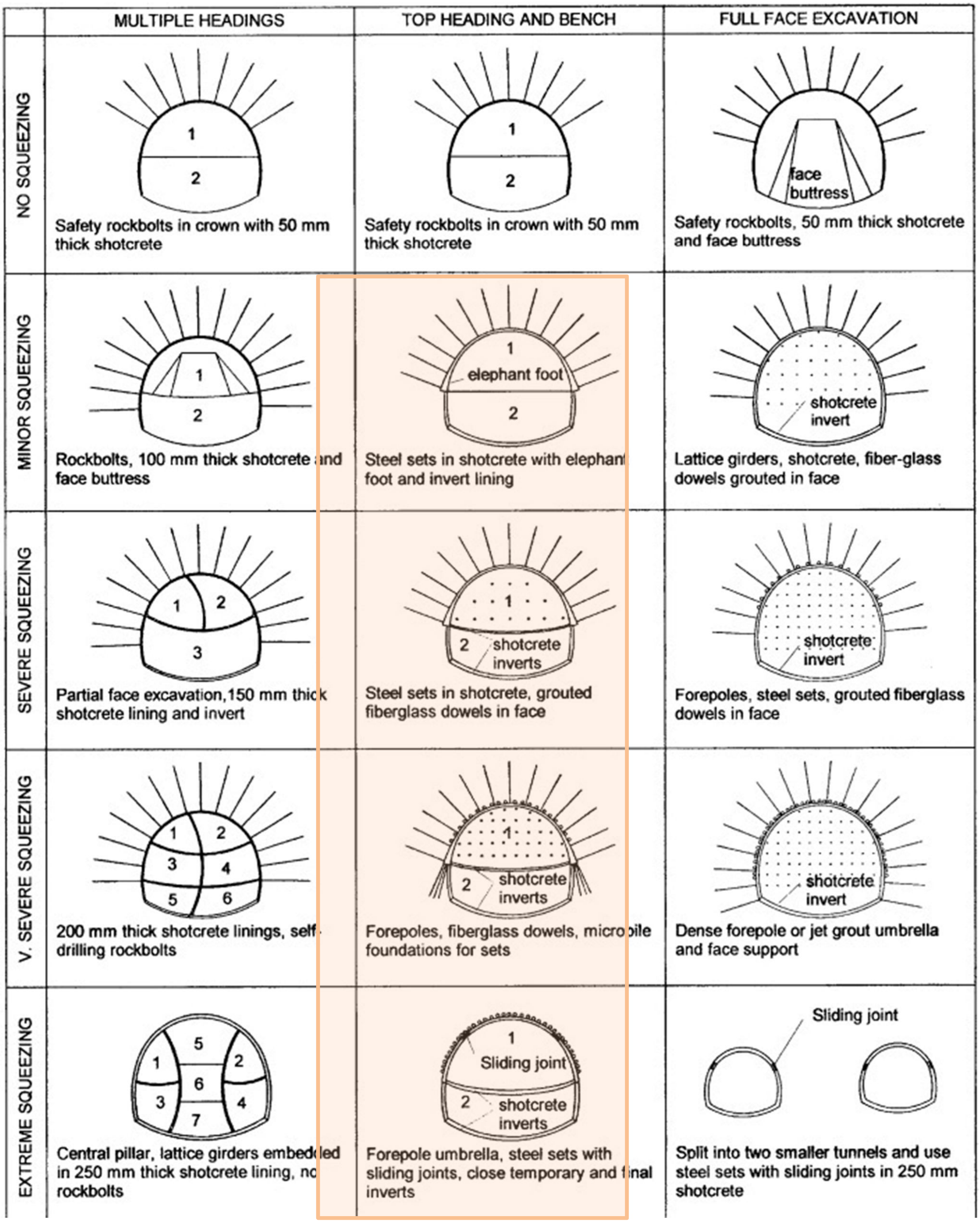


Figure-04, (Hoek (2000) suggestion)

The main focus here is to explore the available solutions for managing squeezing ground conditions and to recommend the most suitable options for different levels of strain. Particularly, the issue of tunnels, with spans ranging from 10 to 16 meters, needs to be considered as they are increasingly common in hydroelectric and transportation projects worldwide.

Methods to handle stability in squeezing ground have mainly been developed in Europe for tunnelling through the Alps (Schubert 1996). These methods fall into three distinct categories. One involves driving small-sized headings ahead of the main face, a method favored by designers north of the Alps, as smaller faces require less support, and the sequential construction creates a strong shotcrete shell. The alternative approaches, typically used by designers south of the Alps, involve driving a tunnel full-face or by top heading and bench excavation, relying on face reinforcement and the surrounding rock mass for stabilization.

B. Empirical Method as per V. Marinos

In an article published in the journal *Environmental and Engineering Geoscience*, Volume XVIII, Issue No. 4, on pages 327 to 341, V. Marinos, an Assistant Professor at Aristotle University of Thessaloniki in Greece, provides a comprehensive analysis of the support systems required for various geological formations. The study emphasizes the importance of tailoring support systems to the specific behaviour types of geological materials encountered in engineering projects. Based on his research findings, Professor Marinos has recommended the following support systems for different behaviour types:

INDICATIVE TUNNEL SUPPORT MEASURES FOR EACH TUNNEL BEHAVIOUR TYPE*

	St	Wg	Ch	Rv	Sh	Sq
Excavation step	>3m in Top heading	2-3m in Top heading	1.5-2.0m in Top heading	1-1.5m in Top heading	1.5-2m	1m
Shotcrete	5 - 7cm	5-10cm	10-15cm	20-25cm	20-25cm	35-70cm**
Bolts	Locally when necessary	Sparse pattern (e.g. 3m x 3m) length and strength according to block volume and weight, fully grouted or friction bolts if there is need for immediate action	Dense pattern (e.g. 1.5m x 1.5m), friction bolts	Dense pattern (e.g. 1.5m x 1.5m), fully grouted.	1.5-2m x 1.5-2m, fully grouted 5-6m length, friction bolts for immediate action	1-1.5m x 1-1.5m, fully grouted 6-9m length in tunnel vault, friction bolts for immediate action. Self drilling bolts may be necessary.
Steel sets		HEB120 or equivalent Lattice Girders Implementation according to rock mass fracturing	HEB120-140 or equivalent Lattice Girders with elephant foot or steel sets embedded in shotcrete	HEB120-140 or equivalent Lattice Girders with elephant foot sets are embedded in shotcrete	HEB120-140 or equivalent Lattice Girders with elephant foot sets are embedded in shotcrete	HEB160-180 or equivalent Lattice Girders with elephant foot sets are embedded in shotcrete
Shell foundation area				Reinforcement may be needed in the foundation area		Micropiles to be considered in case deformations due to subsidence are expected.
Face anchors					The application of fiberglass anchors may be required	Fiberglass anchors are required
Spiles - Forepolling			Φ25-32mm, 5-6m length. Spacing is important to contain the small rock fragments from falling	Spiles or forepoles, 5-6m length. Spacing is important to contain the small rock fragments from falling. If rock fragments are very small, they fall between the spiles and forepolling is necessary.		Φ114, 12m length for face stability problems can be considered
Face buttress			Probable. 5cm shotcrete	Yes with 5cm shotcrete	Probably yes when the rock mass has poor structure	Yes when the rock mass has poor structure
Temporary invert for the top heading				To be considered	To be considered (σ_{cm}/p_o<0.4)	Yes
Permanent invert					To be considered (σ_{cm}/p_o<0.4)	Yes
Drainage		According to groundwater presence	Necessary if groundwater present	Pre-drainage with the presence of water	Drainage relief holes	Drainage relief holes
General remarks	Simple support measures are required	Tunnel step must be decided from the need to confine the wedge failures and from the stand-up time. Immediate application to restrain the rock blocks. Friction bolts have the advantage of immediate action (e.g. Swellex or split set type)	A smaller excavation step can help with the confinement of the rock mass and prevent chimney type failures. Drill and blast must be careful implemented. Immediate application of shotcrete to restrain the rock blocks and prevent subsequent gravity failures from the surrounded rock mass. The philosophy of bolting here is to create a dense pattern where grouting must be performed through bolts. Length is not as crucial as the pattern. Self-drilling anchors may be necessary. Steel sets must be well embedded in shotcrete (Lattice girders help here)	The short step of tunnel advance can help in the confinement of the rock mass and to prevent a wider gravity failure. Immediate shotcrete application to seal the rock mass and constrain it from raveling. The use of closely spaced wire mesh is recommended for immediate restraint of the loose rock "cubes". Self-drilling anchors are needed because the hole instantly collapses. Grouting the surrounded rock mass, to increase its cohesion, can be performed through perforated spiles or forepolles. There is no need for a very heavy support shell if confinement and interlocking is secured	The accurate shotcrete thickness, bolt lengths and strength characteristics are defined from the in situ conditions and the rockmass strength.	**The accurate shotcrete thickness, bolt lengths and strength characteristics are defined according to the squeezing magnitude. Alternatively, very dense bolt pattern around the tunnel vault and sides, a great number of fiberglass bolts at the face and fast closure of the top heading with a temporary invert. -In cases where temporary invert and face support measures cannot control the deformations, fast closure of the tunnel ring with a permanent invert can be implemented. A more circular tunnel shape improves-stability. When σ_{cm}/p_o<0.2 and squeezing problems are very severe, flexible support system with yielding elements should be considered.

***Notes:**
-The specific support measures and loads must be calculated numerically through detailed design analysis
-The principle of the proposed support measures is to contain and control the specific mechanism of failure
- These suggestions can be applied for tunnels of about 10-12m diameter, with conventional excavation by Top Heading and Bench, for depths up to several hundred meters
- Based on analysis of Egnatia Highway tunneling experience

Figure-05 (V. Marinos, support systems required for various geological formations)

C. Empirical Method as per Austrian literature

According to a study grounded in Austrian engineering practices, recommendations have been made regarding the implementation of support systems tailored to various ground types and ground cover conditions. The study provides detailed guidelines for selecting the appropriate support systems to ensure stability and safety in construction and geological projects. The recommendations are as follows:

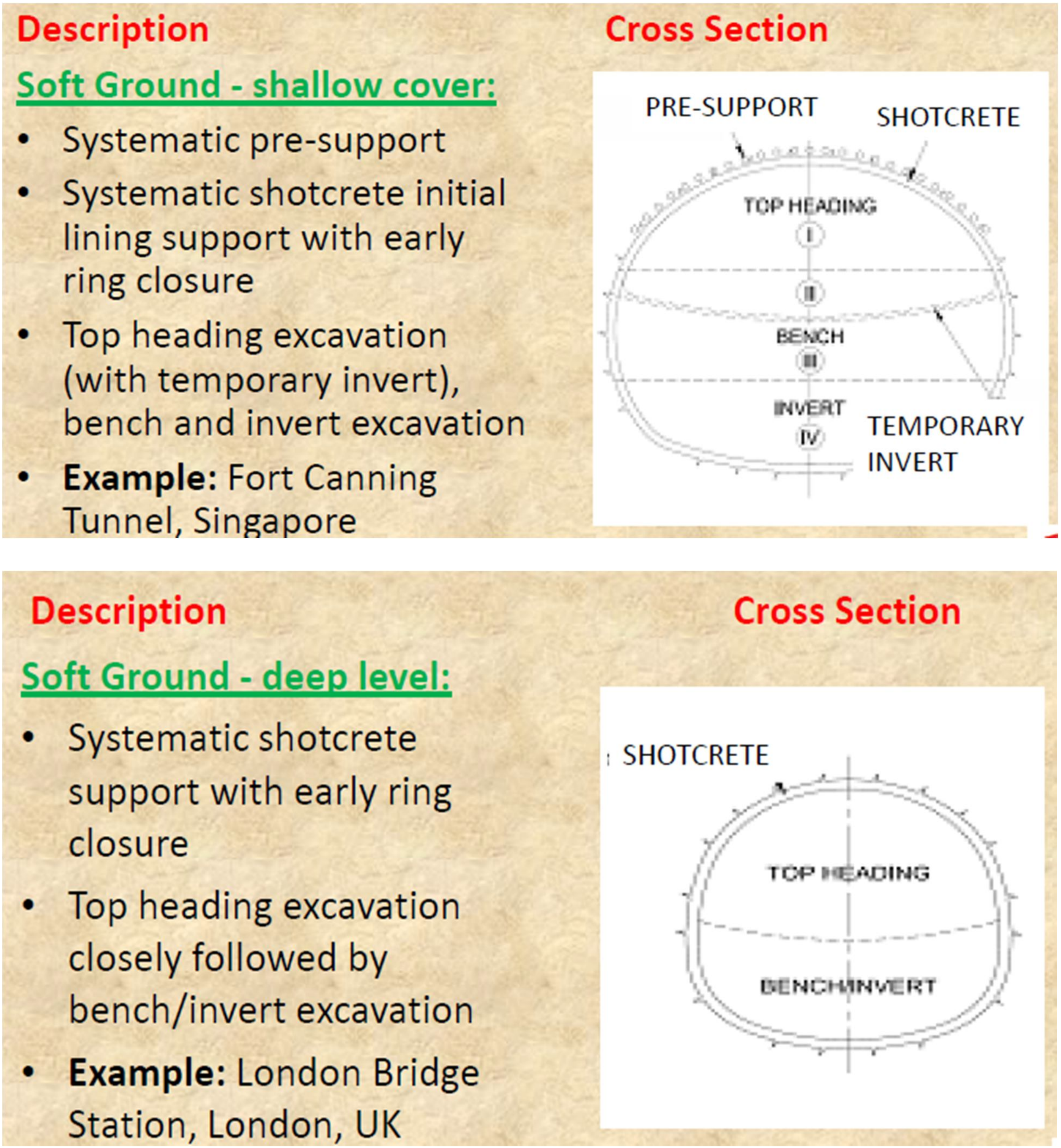


Figure-06

D. Empirical Method as per Ruso et al (2007)

The process of identifying primary support components for rock masses involves using quantitative indexes to describe the different behaviour categories of the rock are shown in below figure-07. According to Russo et al. (2007), these indexes provide a systematic way to categorize and evaluate the behaviour of rock masses under various conditions. By analyzing these indexes, engineers can determine the most suitable support components needed to maintain stability and safety in geological and engineering projects. The quantitative indexes consider factors such as rock strength, deformation characteristics, and stress conditions, allowing for a precise and tailored approach to rock support system design.

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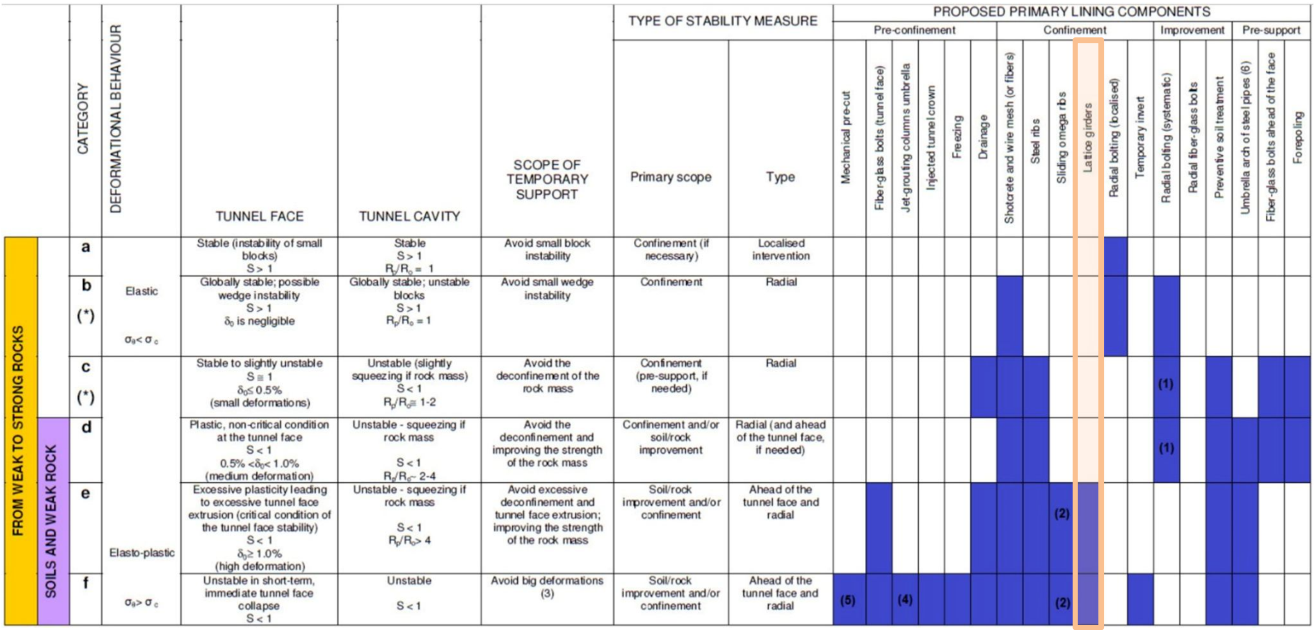


		CATEGORY	DEFORMATIONAL BEHAVIOUR	TUNNEL FACE	TUNNEL CAVITY	SCOPE OF TEMPORARY SUPPORT	TYPE OF STABILITY MEASURE: Primary scope	TYPE OF STABILITY MEASURE: Type
FROM WEAK TO STRONG ROCKS		a	Elastic $\sigma_\theta < \sigma_c$	Stable (instability of small blocks) S > 1	Stable S > 1 R_p/R_o = 1	Avoid small block instability	Confinement (if necessary)	Localised intervention
FROM WEAK TO STRONG ROCKS		b (*)	Elastic $\sigma_\theta < \sigma_c$	Globally stable; possible wedge instability S > 1 δ_0 is negligible	Globally stable; unstable blocks S > 1 R_p/R_o = 1	Avoid small wedge instability	Confinement	Radial
FROM WEAK TO STRONG ROCKS		c (*)	Elasto-plastic $\sigma_\theta > \sigma_c$	Stable to slightly unstable S ≅ 1 $\delta_0 \leq 0.5\%$ (small deformations)	Unstable (slightly squeezing if rock mass) S < 1 $R_p/R_o \cong$ 1-2	Avoid the deconfinement of the rock mass	Confinement (pre-support, if needed)	Radial
FROM WEAK TO STRONG ROCKS	SOILS AND WEAK ROCK	d	Elasto-plastic $\sigma_\theta > \sigma_c$	Plastic, non-critical condition at the tunnel face S < 1 $0.5\% < \delta_0 < 1.0\%$ (medium deformation)	Unstable - squeezing if rock mass S < 1 $R_p/R_o \sim$ 2-4	Avoid the deconfinement and improving the strength of the rock mass	Confinement and/or soil/rock improvement	Radial (and ahead of the tunnel face, if needed)
FROM WEAK TO STRONG ROCKS	SOILS AND WEAK ROCK	e	Elasto-plastic $\sigma_\theta > \sigma_c$	Excessive plasticity leading to excessive tunnel face extrusion (critical condition of the tunnel face stability) S < 1 $\delta_0 \geq 1.0\%$ (high deformation)	Unstable - squeezing if rock mass S < 1 $R_p/R_o > 4$	Avoid excessive deconfinement and tunnel face extrusion; improving the strength of the rock mass	Soil/rock improvement and/or confinement	Ahead of the tunnel face and radial
FROM WEAK TO STRONG ROCKS	SOILS AND WEAK ROCK	f	Elasto-plastic $\sigma_\theta > \sigma_c$	Unstable in short-term, immediate tunnel face collapse S < 1	Unstable S < 1	Avoid big deformations (3)	Soil/rock improvement and/or confinement	Ahead of the tunnel face and radial

CATEGORY	PROPOSED PRIMARY LINING COMPONENTS: Pre-confinement						Confinement						Improvement			Pre-support		
	Mechanical pre-cut	Fiber-glass bolts (tunnel face)	Jet-grouting columns umbrella	Injected tunnel crown	Freezing	Drainage	Shotcrete and wire mesh (or fibers)	Steel ribs	Sliding omega ribs	Lattice girders	Radial bolting (localised)	Temporary invert	Radial bolting (systematic)	Radial fiber-glass bolts	Preventive soil treatment	Umbrella arch of steel pipes (6)	Fiber-glass bolts ahead of the face	Forepoling
a																		
b																		
c													(1)					
d													(1)					
e									(2)									
f	(5)		(4)						(2)									

Figure-07 (According to Russo et al. (2007)

E. Finding

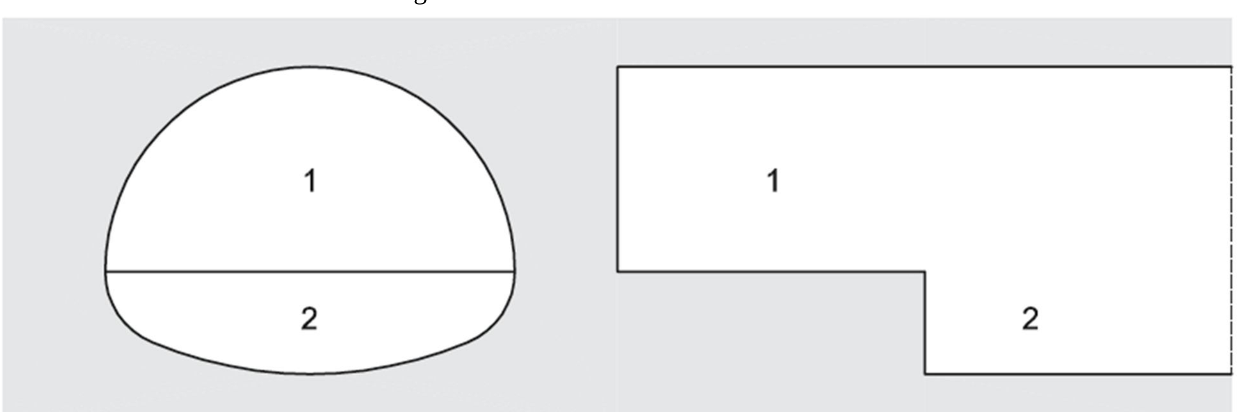
Four empirical methods have been discussed above, each recommended based on the extensive experience of the experts who developed them. However, when applied to real-world projects, conflicts often arise between the detailed design consultant and the proof consultant regarding the selection and implementation of these methods.

VI. ANALYTICAL METHOD

In tunnelling, the design and stability of the tunnel structure are paramount. The analytical methods to calculate the requirements for components like the elephant foot, temporary invert, and permanent invert are critical for ensuring the tunnel's safety and longevity.

A. Analytical Calculation Method

As per the Book Dimitrios Kolymbas - Tunelling and tunnel mechanics a rational approach to tunnelling-Springer (2008), he has mentioned that the temporary support of the crown with shotcrete can be conceived as a sort of arch bridge (Figure-08). This explains why the abutments are prone to settlements, which induce settlements of the ground surface. Countermeasures are to enlarge the abutments (so-called elephant feet), to strengthen them with micro piles or the construction of a temporary invert. The latter must be constructed soon after the heading of the crown.



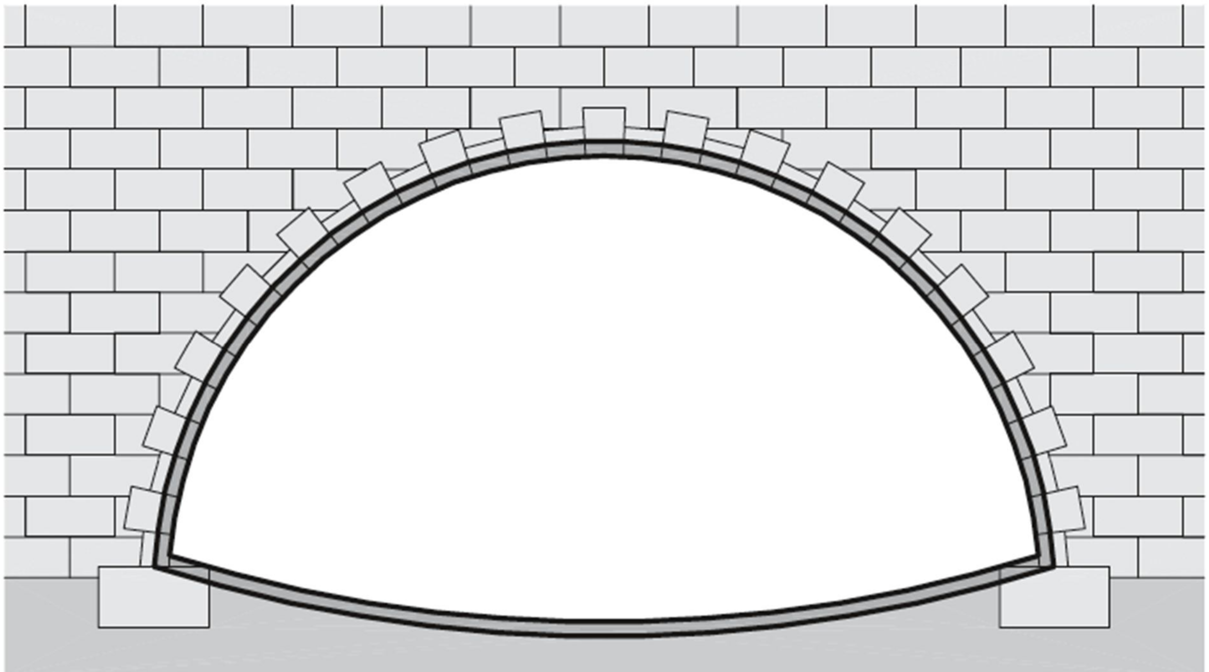


Figure-08 (Concept of crown support)

In top heading the upper part of the tunnel is excavated first and supported with shotcrete lining. This lining constitutes a sort of arch (or bridge) whose footings must be safely founded, i.e. the vertical force F exerted by the body ABCD (Fig. 9) has to be introduced into the subsoil. To assess the safety against punching of the footings into the subsoil, F is estimated by means of Janssens equation.

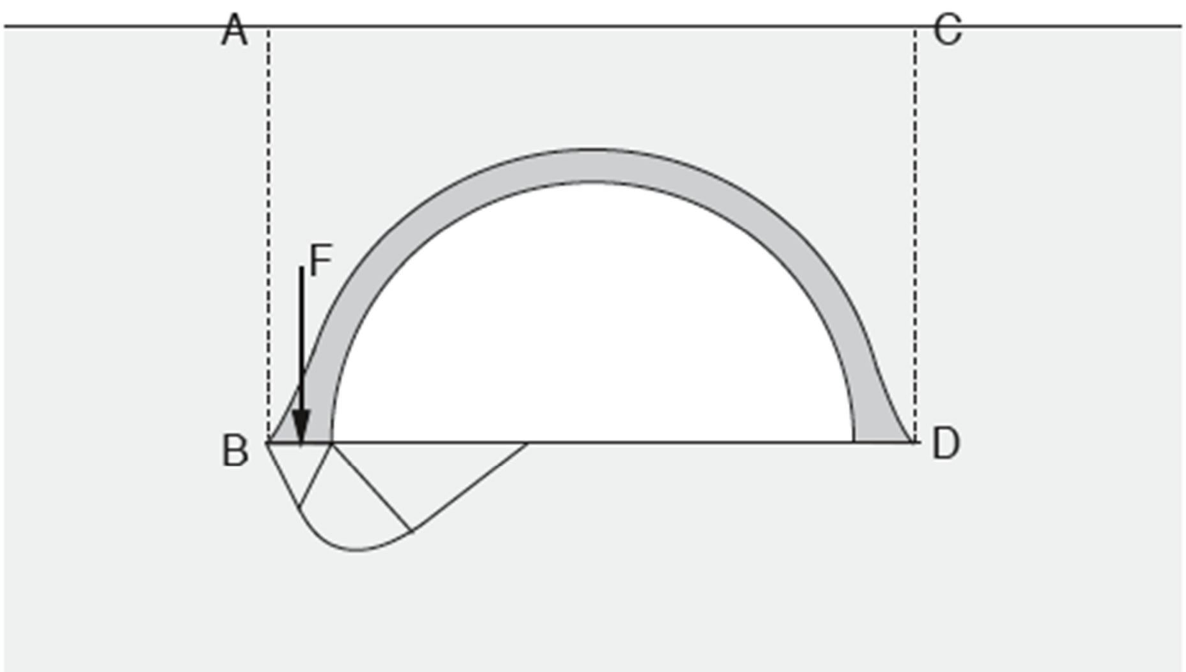


Figure-09

The bearing capacity of the ground has been calculated considering the C value=40kpa and angle of friction is 30^0.

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The rock load exerted on both sides of the tunnel wall, particularly at the shoulder areas, has been calculated using Terzaghi's formula. This calculation accounts for varying depths of ground cover above the tunnel. Furthermore, the pressure at the junction between the tunnel heading and the benching has been carefully analysed.

Based on the analytical calculations, which are derived from the book 'Tunnelling and Tunnel Mechanics: A Rational Approach to Tunnelling' by Dimitrios Kolymbas (Springer, 2008), the findings have been compiled and are presented in the table below.

Sr no	Ground cover in miter	Capacity of ground Bearing capacity) in (KPA)	Ground load on shoulder in Kn	Ground pressure below the initial lining considering thickness 250mm	Remarks
1	25m	4128	362.2	8692.8	Capacity of ground is less than the acting ground pressure at desired location
2	50m	7745	569.5	13668	
3	75m	11362	688.1	16514.4	
4	100m	14979	7559.9	181437.6	

Analytical calculations have indicated that the ground pressure at the heading and benching junction exceeds the bearing capacity of the ground at that level. To address this issue, it is recommended to incorporate an 'elephant foot' structure to distribute the load over a wider area, thereby enhancing stability and preventing potential ground failure.

VII. NUMERICAL METHOD

A. Computation Process

The computation process involves several stages, each corresponding to different phases of tunnel construction. These stages are crucial for accurately modelling the stress and strain state around the excavated tunnel, as well as the forces acting on the lining. The staged approach allows for a more realistic simulation of tunnel behavior as construction progresses.

B. Deconfinement Ratio

To accurately calculate the deconfinement ratio at the point where the support is installed (1.5 meters from the tunnel face), a specific graph has been used. This graph, which is included in the figure below, is derived from the publication by Celada in Ingeotúneles, Vol. 7 (2004). The graph provides a relationship between the distance from the tunnel face and the corresponding deconfinement ratio, based on empirical data and theoretical analysis. By referencing this graph, engineers can determine the appropriate deconfinement ratio for the support installation position, ensuring that the support system is designed to handle the expected loads and ground movements.

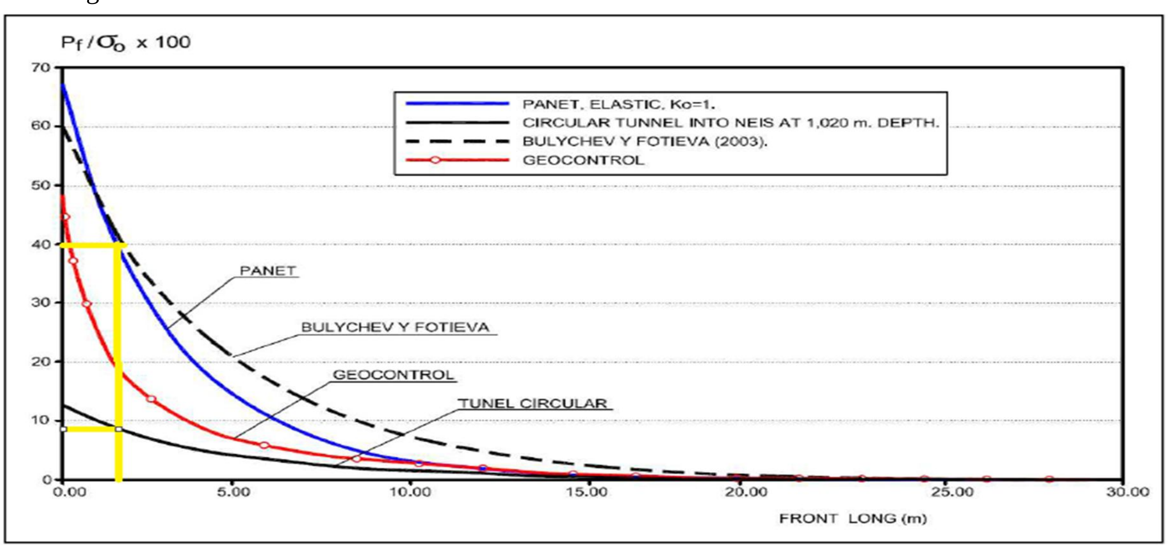

Figure-33

So the Deconfinement Ratio 0.4 has been considered in the analysis.

As mentioned above the same has been simulated with RS-2 software and stage analysis has been performed.

The typical NATM excavation and support system activation procedure are mentioned in below figure-34 and in the same line has been simulated.

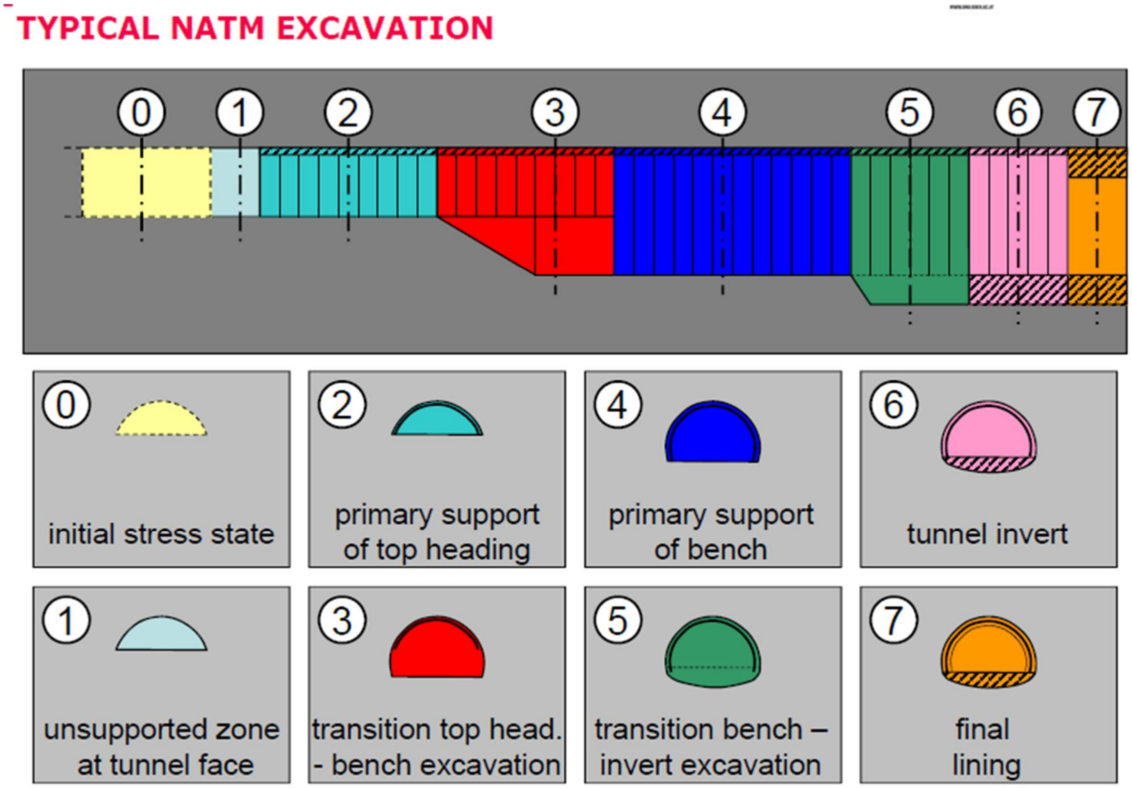

Figure-34

The following stage has been considered in preliminary design

Step-1; Insitu stress condition.

Step-2; Top-heading excavation and relaxation of rock mass

Step-3; Support activation.

Step-4; Bottom excavation and relaxation of rock mass

Step-5; Support activation in bottom.

A total of 24 Finite Element Method (FEM) analyses were conducted using the RS2 software. These analyses were performed under varying conditions to assess the impact of different parameters on tunnel stability. The conditions considered in these analyses included varying depths (25m, 50m, 75m, and 100m) and two different values of the earth pressure coefficient (K0) =0.5 and K0=1.

A. Key Parameters and Configurations

The analyses were further differentiated by the inclusion or exclusion of specific structural features within the tunnel .i.e. Elephant Foot Inclusion, Temporary Invert Inclusion

B. Analysis Objectives

The goal of these analyses was to understand how these different configurations, varying depths, Varying K0 values, presence of an elephant foot, and temporary invert affect, the stress distribution, deformation, and overall stability of the tunnel. By considering a wide range of conditions, the study aimed to provide comprehensive insights into the behaviour of tunnels under different geotechnical scenarios.

All 24 no's of analysis are tabulated below;

1. Analysis-1, Ko=0.5, Ground Cover -25m.
2. Analysis-2, Ko=0.5, Ground Cover -50m.
3. Analysis-3, Ko=0.5, Ground Cover -75m.

4. Analysis-4, Ko=0.5, Ground Cover -100m.
5. Analysis-5, Ko=1.0, Ground Cover -25m.
6. Analysis-6, Ko=1.0, Ground Cover -50m.
7. Analysis-7, Ko=1.0, Ground Cover -75m.
8. Analysis-8, Ko=1.0, Ground Cover -100m.
9. Analysis-9, Ko=0.5, With Elephant Foot-Ground Cover -25m.
10. Analysis-10, Ko=0.5, With Elephant Foot- Ground Cover -50m.
11. Analysis-11, Ko=0.5, With Elephant Foot- Ground Cover -75m.
12. Analysis-12, Ko=0.5, With Elephant Foot-Ground Cover -100m.
13. Analysis-13, Ko=1.0, With Elephant Foot- Ground Cover -25m.
14. Analysis-14, Ko=1.0, With Elephant Foot- Ground Cover -50m.
15. Analysis-15, Ko=1.0, With Elephant Foot- Ground Cover -75m.
16. Analysis-16, Ko=1.0, With Elephant Foot- Ground Cover -100m.
17. Analysis-17, Ko=0.5, With Elephant Foot and Temporary Invert-Ground Cover -25m.
18. Analysis-18, Ko=0.5 With Elephant Foot and Temporary Invert- Ground Cover -50m.
19. Analysis-19, Ko=0.5 With Elephant Foot and Temporary Invert-Ground Cover -75m.
20. Analysis-20, Ko=0.5 With Elephant Foot and Temporary Invert--Ground Cover -100m.
21. Analysis-21, Ko=1.0, With Elephant Foot and Temporary Invert- Ground Cover -25m.
22. Analysis-22, Ko=1.0, With Elephant Foot and Temporary Invert-Ground Cover -50m.
23. Analysis-23, Ko=1.0, With Elephant Foot and Temporary Invert- Ground Cover -75m.
24. Analysis-24, Ko=1.0, With Elephant Foot and Temporary Invert- Ground Cover -100m.

The above analysis has been done considering Tunnel strain (Critical Strain) is defined as the ratio of tunnel convergence to tunnel diameter. Sakurai (1983) proposed that the stability of tunnels could be assessed based on the strain in the surrounding rock mass. A critical strain threshold of approximately 2% is often used to delineate the boundary between stable tunnels, which require minimal support, and unstable tunnels, which necessitate special consideration in support design. This concept has been validated in numerous practical tunnel applications, indicating that tunnel stability issues tend to escalate as strain levels increase (Hoek, 1999).

➢ Analysis-1, Ko=0.5, Ground Cover -25m.

Result

- Yielded Elements reaching ground level indicate the loss of natural ground support, meaning the arching effect is no longer working, which can lead to cavity formation and serious structural instability.
- Strain reaching 3%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis-2, Ko=0.5, Ground Cover -50m.

Result

- Yielded Elements is high that l indicate the loss of natural ground support, which can lead to cavity formation and serious structural instability.
- Strain reaching 3%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis-3, Ko=0.5, Ground Cover -75m.

Result

- Yielded Elements is high that l indicate the loss of natural ground support, which can lead to cavity formation and serious structural instability.
- Strain reaching 5%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis-4, Ko=0.5, Ground Cover -100m.

Result

- Yielded Elements is high that l indicate the loss of natural ground support, which can lead to cavity formation and serious structural instability.
- Strain reaching 7.5%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis-5, Ko=1.0, Ground Cover -25.0m.

Findings

- Yielded Elements is high that l indicate the loss of natural ground support, which can lead to cavity formation and serious structural instability.
- Strain reaching 2.5%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis-6, Ko=1.0, Ground Cover -50.0m.

Result

- Yielded Elements is high that l indicate the loss of natural ground support, which can lead to cavity formation and serious structural instability.
- Strain reaching 4%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis-7, Ko=1.0, Ground Cover -75.0m.

Result

- Yielded Elements is high that l indicate the loss of natural ground support, which can lead to cavity formation and serious structural instability.
- Strain reaching 6%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis-8, Ko=1.0, Ground Cover -100.0m.

Result

- Yielded Elements is high that l indicate the loss of natural ground support, which can lead to cavity formation and serious structural instability.
- Strain reaching 10%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis-9, Ko=0.5, With Elephant Foot-Ground Cover -25m.

Result

Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.

- Strain reaching 1%, which is well within the critical strain of 2%.
- So considered elephant in analysis is effective that reduced strain as well as yielding of ground around the periphery of excavation

➢ Analysis-10, Ko=0.5, With Elephant Foot-Ground Cover -50m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain reaching 1.5%, which is well within the critical strain of 2%.
- So considered elephant foot in analysis is effective that reduced strain as well as yielding of ground around the periphery of excavation

➢ Analysis-11, Ko=0.5, With Elephant Foot-Ground Cover -75.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.

- Strain reaching 3.0%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis-12, Ko=0.5, With Elephant Foot-Ground Cover -100.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain reaching 3.5%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis - 13, Ko=1.0, With Elephant Foot - Ground Cover - 25.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain reaching 0.75 %, which is well within the permissible critical strain of 2%.

➢ Analysis - 14, Ko=1.0, With Elephant Foot - Ground Cover - 50.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain reaching 1.5 %, which is well within the permissible critical strain of 2%.

➢ Analysis - 15, Ko=1.0, With Elephant Foot - Ground Cover - 75.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain reaching 4%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis - 16, Ko=1.0, With Elephant Foot - Ground Cover - 100.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain reaching 5 %, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

➢ Analysis - 17, Ko=0.5, With Elephant Foot as well as temporary invert - Ground Cover - 25.0m.

Results

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain is o.7% that is well within the permissible critical strain of 2%.

➢ Analysis - 18, Ko=0.5, With Elephant Foot as well as temporary invert - Ground Cover - 50.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain is 1.5 % that is well within the permissible critical strain of 2%.

➢ Analysis - 19, Ko=0.5, With Elephant Foot as well as temporary invert - Ground Cover - 75.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain is approximate 2% that is approximate within the permissible critical strain of 2%.

- Analysis - 20, Ko=0.5, With Elephant Foot as well as temporary invert - Ground Cover - 100.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain reaching 4%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

- Analysis - 21, Ko=1.0, With Elephant Foot as well as temporary invert - Ground Cover - 25.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain is 0.7% that is well within the permissible critical strain of 2%.

- Analysis - 22, Ko=1.0, With Elephant Foot as well as temporary invert - Ground Cover - 50.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain is 1.83% that is well within the permissible critical strain of 2%.

- Analysis - 23, Ko=1.0, With Elephant Foot as well as temporary invert - Ground Cover - 75.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain reaching 3%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

- Analysis - 24, Ko=1.0, With Elephant Foot as well as temporary invert - Ground Cover - 100.0m.

Result

- Yielded Elements is not much high in this condition and not touching the ground level, which can't lead to cavity formation and serious structural instability.
- Strain reaching 6%, which is above the critical strain of 2%, suggests that the rock mass is deforming excessively and is at risk of failure.

VIII. GENERAL FINDINGS

This document summarizes the requirements for implementing an elephant foot, temporary invert, and permanent invert in engineering projects involving ground cover, particularly in tunneling and excavation contexts. The calculations and recommendations stem from theoretical analyses as well as empirical data, focusing on different depths of ground cover.

A. Empirical method as per Hoek 2000

- According to the empirical calculations from Hoek (2000), for a ground cover of 25.0 M, neither an elephant foot nor a temporary invert is necessary.
- Findings: Hoek (2000) indicates that, at 50.0 M, only an elephant foot is required.
- At 75.0 M of ground cover, empirical calculations suggest that both an elephant foot and a temporary invert are necessary, according to Hoek (2000).
- Hoek (2000) further notes that for 100.0 M of ground cover, both elements remain essential.

B. Empirical method as per V. Marinos

- Findings: Empirical calculations presented by V. Marinos indicate that in all cases evaluated, both an elephant foot and a temporary invert are essential.

C. Empirical method as per Russo et al. 2007

- Findings: Russo et al. (2007) emphasize that for ground covers exceeding 50.0 M, a temporary invert is required.

D. Analytical calculation

As per analytical calculation, in all cases the bearing capacity of the ground is less that the pressure just below the heading benching junction so elephant foot required.

IX. NUMERICAL CALCULATIONS

1) Numerical analyses consistently show that an elephant foot is required across all scenarios.
2) For ground covers greater than 50.0 M, both the elephant foot and temporary invert are necessary.
3) When considering ground cover greater than 75.0 M, applying a temporary invert requires the use of both an elephant foot and a permanent invert to manage strains effectively at critical levels.

X. CONCLUSION

The necessity and functionality of the elephant foot, temporary invert, and permanent invert in engineering practices depend significantly on the depth of ground cover and the associated geological conditions.

The choice of method depends on several factors such as the complexity of the ground conditions, the availability of data, and the resources available for the project. Often, a combination of these methods is used to achieve a reliable and robust design.

Empirical Method Suitable for preliminary design and in cases where quick decisions are needed. Analytical Method Useful for straightforward conditions and where detailed theoretical understanding is beneficial. Numerical Method Ideal for complex ground conditions and when detailed, accurate predictions are necessary.

By combining these methods, engineers can develop a comprehensive understanding of the support requirements for a tunnel, ensuring safety and stability throughout the construction and operational phases.

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